

# A Large-Scale Search for Dark-Matter Axions

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## A LARGE-SCALE SEARCH FOR DARK-MATTER AXIONS

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We review the status of two ongoing large-scale searches for axions which may constitute the dark matter of our Milky Way halo. The experiments are based on the microwave cavity technique proposed by Sikivie, and marks a 'second-generation' to the original experiments performed by the Rochester-Brookhaven-Fermilab collaboration, and the University of Florida group.

## 1 INTRODUCTION

Axions, a promising cold dark matter candidate, arise from a minimal extension of the Standard Model to enforce Strong-CP conservation. The Peccei-Quinn solution to the Strong-CP problem in QCD<sup>1</sup> involves an approximate  $U_{PQ}(1)$  global symmetry which is spontaneously broken at some unknown symmetry-breaking scale  $f_a$ . The axion is the associated pseudo-Goldstone Boson.<sup>2</sup>

The properties of the axion depend mainly on the symmetry breaking scale  $f_a$ . Its mass is given by

$$m_a[\text{eV}] \approx 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a [\text{GeV}]} \quad (1)$$

All of the axions couplings are proportional to  $m_a$ . The coupling relevant for cavity detectors is the two-photon coupling described by

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha \phi_a}{4\pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} \phi_a \mathbf{E} \cdot \mathbf{B} \quad (2)$$

where  $\alpha$  is the fine structure constant,  $\phi_a$  is the axion field,  $g_\gamma$  is a model-dependent constant of order unity, and  $g_{a\gamma\gamma} = (\alpha g_\gamma / \pi f_a)$ . For the two most important axion models, KSVZ<sup>3</sup> and DFSZ<sup>4</sup>,  $g_\gamma \sim 0.97$ , and  $g_\gamma \sim -0.36$  respectively.

Since  $f_a$  is unknown and arbitrary,  $m_a$  could have any value. Fortunately, astrophysical and cosmological considerations help constrain  $m_a$ . The presently allowed mass

range, or axion window is  $1 \mu\text{eV} < m_a < 10 \text{ meV}$ .<sup>5,6</sup>

## 2 THE MICROWAVE CAVITY AXION DETECTOR

To date, the most efficient method of searching for axions is the microwave cavity technique originally proposed by Sikivie.<sup>8</sup> In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by  $hf = m_a c^2 (1 + O(10^{-6}))$ . A high-Q resonant cavity, tuned to the axion mass serves as the detector for the converted photons. The expected signal power varies with the experimental parameters as<sup>8,9</sup>

$$P_{a \rightarrow \gamma} \propto B^2 V C Q f \rho_a \quad (3)$$

where  $B$  is the background magnetic field,  $V$  is the cavity volume,  $C$  is a mode dependent form factor,  $Q$  is the loaded quality factor,  $f$  is the resonant frequency, and  $\rho_a$  is the local halo axion density. For the parameters of the U.S. experiment, the power from KSVZ axions is typically  $5 \times 10^{-22} \text{ W}$ .

Since the axion mass is unknown, the frequency of the cavity must be tunable. The scan rate scales as

$$\frac{df}{dt} \propto \frac{f_o^2 Q_u C^2 B^4 V^2}{T_s^2} \quad (4)$$

where  $T_s$  is the system noise temperature.

### 3 THE U.S. DARK-MATTER AXION SEARCH

This section describes the operations and results of a microwave cavity axion search currently operating at Lawrence Livermore National Laboratory. This experiment, a collaboration of LLNL, MIT, Univ. of Florida, LBNL, UCB, Univ. of Chicago, and FNAL, has been operating with greater than 90% live time since February 1996 exploring the region from 0.3 to 3.0 GHz (1.2 to 12.4  $\mu\text{eV}$ ) at better than KSVZ sensitivity.<sup>10</sup> The experiment draws heavily on the experience gained in two pilot experiments performed in the late 1980's, one by a collaboration of Rochester-Brookhaven-Fermilab (RBF)<sup>11</sup> and a second at the University of Florida (UF).<sup>12</sup>

Figure 1 is a schematic of the U.S. dark-matter axion detector.

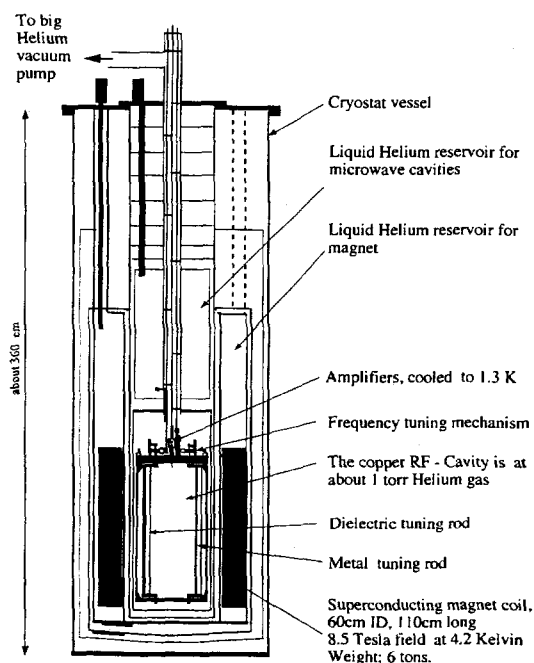


Figure 1. The U.S. Axion search detector.

The magnet employed in this search is a superconducting NbTi solenoid constructed by Wang NMR Inc.<sup>13</sup> The operating field at the center of the coil is usually 7.62 T.

The microwave cavities are right-circular cylinders constructed from stainless steel and copper plated. Two different cavity configurations have been used so far in this experiment. The region from 550 - 810 MHz has been scanned with a single cavity 50 cm in diameter and 1 m long. Recently, a set of four identical cavities has been operated with the output combined in phase using a Wilkinson power combiner. Each cavity has a 20 cm diameter and is 1 m long. The four-cavity array will be used to search from 810-2000 MHz.

Power-combining multiple cavities allows the entire magnet volume to be utilized as the frequency of the cavities increases. This is possible because the axion signal is coherent on laboratory scales ( $\lambda_D \approx 10\text{-}100\text{ m}$ ).

Moving a combination of metal and dielectric rods, running the full length of the cavities, changes the resonant frequency. These rods can move from the center of the cavity to the wall. The single cavity rods were moved using stepper motors followed by a gear reduction of 42000:1. The final step size was approximately 600 nm, corresponding to roughly 500 Hz frequency shifts. This mechanical system was not practical for the four-cavity array, so a new piezoelectric based mechanism was implemented. The stepping resolution with this system was better than 50 nm, corresponding to a frequency resolution better than 100 Hz. All four cavities must have the same frequency for optimal phase-matching.

The cryogenic amplifiers used in this search are double-balanced GaAs HFET amplifiers supplied by NRAO.<sup>14</sup> The *in situ* measured noise temperatures range from 1.7 - 4.5 K.

A double-heterodyne receiver mixes a small bandwidth centered on the cavity frequency down to 35 kHz. This audio fre-

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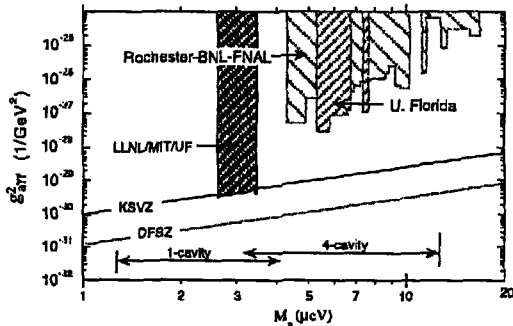


Figure 2. Axion couplings and masses excluded at the 90% confidence level by the U.S. experiments. The solid lines indicate the KSVZ and DFSZ model predictions. The arrows at the bottom indicate the coverage of different cavity configurations. The results from the two pilot experiments are scaled to 90% c.l. and  $\rho_a = \rho_{halo}$ .

quency signal is then sent to medium and high-resolution spectrum analyzers.

The medium-resolution search channel consists of a Stanford Research Systems<sup>15</sup> FFT spectrum analyzer with a frequency resolution of 125 Hz. These data are coadded and the result searched for Maxwellian peaks a few bins wide (about 700 Hz) characteristic of thermalized axions in the halo.<sup>16</sup>

An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal.<sup>17,18</sup> The 35 kHz signal passes through a third mixing stage to shift the center frequency to 5 kHz. A PC based DSP takes a single 50 second spectrum and performs an FFT with 20 mHz frequency resolution, about the limit imposed by the Doppler shift due to the earth's rotation. These data are searched for coincidences between different scans, as well as coincidences with peaks in the medium resolution data.

So far, no axion signal has been detected. Based on these results, we exclude at 90% confidence a KSVZ axion of mass between 2.5 and 3.3  $\mu\text{eV}$ , assuming that thermalized axions comprise a major fraction of our galactic halo ( $\rho_a = 450 \text{ MeV}/\text{cm}^3$ ). This exclusion region and the results from two pilot experi-

ments are shown in Figure 2. For more details see Ref. [20].

In March 2000, the first data from the four-cavity array was taken. This was a commissioning run in a region with a low form factor. With the arrival of new HFET amplifiers in the 1-2 GHz region, production running with the four-cavity array will commence in Fall 2000.

## 4 RESEARCH AND DEVELOPMENT

The ultimate goal of this experiment is to scan as much of the axion window as possible with DFSZ sensitivity. Since the expected power from DFSZ axion conversion is an order of magnitude lower than that from KSVZ axions it would take one hundred times longer to reach similar sensitivity. From Equation 4, the scanning rate goes as  $T_s^{-2}$ , therefore, an order of magnitude reduction in system noise temperature would allow a scan at DFSZ sensitivity with the same rate as the present scan with KSVZ sensitivity. This is achievable with new dc SQUID based RF amplifiers.

### 4.1 dc SQUID Amplifiers

In the past two years a group at Berkeley led by John Clarke has developed dc SQUID amplifiers in the 100 - 3000 MHz range specifically for the axion experiment. Noise temperatures as low as 50 mK have been measured at a physical temperature of 30 mK.

The dc SQUID consists of two Josephson junctions connected in parallel on a superconducting loop. The SQUID produces an output voltage in response to a small input flux, and is a very sensitive flux-to-voltage transducer. Detailed computer simulations of the signal and noise properties were made by Tesche and Clarke.<sup>21</sup>

The most common configuration of a dc SQUID amplifier is shown in Figure 3.<sup>22</sup> The superconducting loop is a square washer with a slit on one side. The loop is closed

via a superconducting counter-electrode connected to the washer by two resistively-shunted Josephson junctions. Flux is coupled into the SQUID through a microstrip input coil separated from the washer by a thin insulating layer. A microstrip resonator is formed by the open-ended stripline whose impedance is determined by the inductance of the input coil and its ground plane, and the capacitance between them. Near the fundamental frequency of the stripline, the gain of the amplifier is strongly enhanced.

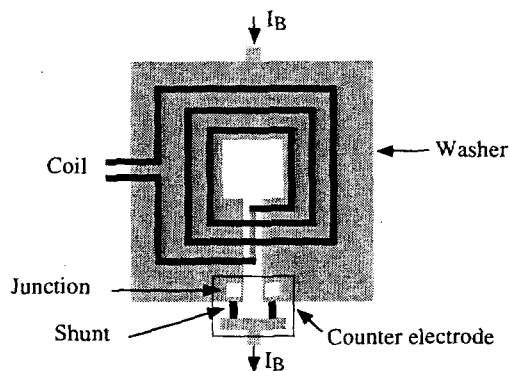


Figure 3. Square-Washer dc SQUID. The signal is coupled to the innermost turn of the coil, the outermost turn is either open-ended, shorted to the washer, or connected to a variable reactance.

The square-washer SQUIDs fabricated at Berkeley had inner and outer dimensions of 0.2 mm x 0.2 mm and 1 mm x 1 mm, and the input coils had a width of 5  $\mu\text{m}$  and lengths ranging from 6 - 71 mm. The resonant frequency of the stripline scales as  $\ell^{-1}$ ; the highest frequency amplifier built so had  $f > 3$  GHz. Frequencies up to 5-7 GHz should be achievable with the same design.

The bandwidth of these amplifiers has been greatly improved by varying the resonant frequency of the stripline *in situ*. This has been accomplished by connecting a pair of GaAs varactor diodes across the previously open end of the microstrip.<sup>23</sup>

The noise temperature of the SQUID amplifiers was measured using a heated resis-

tor. The dominant source of noise in these devices is the Johnson noise from the resistive shunts across the Josephson junctions. This noise scales linearly with temperature, so the noise temperature of dc SQUIDs is expected to be proportional to their physical temperature until either the quantum limit ( $T_a = \hbar\nu/k_B \ln 2$ )<sup>24</sup> is reached or hot electron effects in the shunts become dominant.

In an attempt to reduce the noise temperature, SQUIDs were cooled to 0.4 - 0.5 K in a charcoal-pumped, single-shot <sup>3</sup>He cryostat.<sup>25</sup> The system noise temperature at 438 MHz was  $0.50 \pm 0.07$  K, of which  $0.38 \pm 0.07$  K was contributed by the postamplifier.

At 500 mK, the noise temperatures are already within a factor of four of the quantum limit, which for a 500 MHz amplifier is approximately 35 mK. Demonstrating a quantum limited amplifier will require a much quieter postamplifier. Toward this end, a second SQUID has been used as a postamplifier to the input SQUID. The maximum power gain at 386 MHz was  $33.5 \pm 1$  dB. Noise temperatures below 100 mK have been measured using cascaded SQUIDs cooled in a dilution refrigerator. Work is continuing to demonstrate quantum-limited noise performance.

#### 4.2 Higher Frequency Cavities

Predictions of  $m_a$  from string models are typically  $\mathcal{O}(100 \mu\text{eV})$ , requiring cavities with  $f_{010} \sim 25$  GHz. The technique of power-combining signals from many small cavities is only practical for frequencies up to  $\approx 3$  GHz, because the number of cavities required scales as  $f_{010}^3$ , where  $f_{010}$  is the frequency of the  $\text{TM}_{010}$  mode. An alternative for reaching higher frequencies is the strategic placement of metal posts inside a single larger cavity.<sup>19</sup> If they are practical, these cavities could extend the mass range of microwave cavity axion searches by another decade.

## 5 RYDBERG ATOM SINGLE-QUANTUM DETECTOR

Another second-generation axion search is under development at the University of Kyoto. This effort seeks to exploit the extremely low-noise photon counting capability of Rydberg atoms in a Sikivie-type microwave cavity experiment. The initial goal is to sweep out a 10% mass window around  $2.4\mu\text{eV}$ .

An experiment utilizing Rydberg atom single-quantum detection in Kyoto is well along in commissioning ('CARRACK' for Cosmic Axion Research with Rydberg Atoms in a Resonant Cavity in Kyoto).<sup>27</sup> A sketch of the apparatus is shown in Figure 4. The microwave resonator is a single copper cavity (4.5 cm radius, 72.5 cm long) which fits inside a superconducting solenoid (15 cm diameter, 50 cm long, 7 T peak field). Power from the conversion cavity is coupled to a niobium superconducting cavity just above it, where the magnetic field is canceled by a bucking coil. The frequency of both cavities are made to track by means of 6 mm sapphire rods inserted axially into them. The cavities are cooled to  $< 15$  mK by means of a dilution refrigerator.

A beam of rubidium atoms is accelerated, neutralized and directed vertically through the detection cavity. Just before entering the detection cavity, the atoms are excited to a Rydberg state with principal quantum number near 160, by triple optical excitation with three colinear diode laser beams. In the detection cavity, the Rydberg atoms are then Stark-tuned so an  $E1\ np \rightarrow (n+2)s$  transition is matched to the cavity frequency. After exiting, the Rydberg atoms are selectively ionized by an electric field (around 0.5 V/cm) and the liberated electron is detected and amplified by an electron multiplier ("Channeltron").

Studies have been performed to confirm that the experiment is sensitive to single

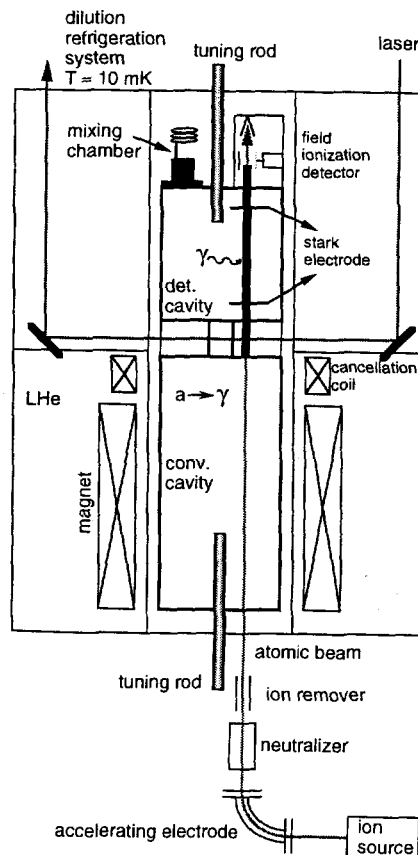


Figure 4. Schematic diagram of the experimental system to search for axions with Rydberg atoms in cooled resonant cavities.

blackbody photons in the  $< 15$  mK range. These include verifying the temperature dependence, and the number and velocity of the Rydberg atoms.<sup>28</sup> Several percent of mass range around 2.4 GHz ( $\sim 10\mu\text{eV}$ ) has been swept out, but candidate peaks have not been eliminated yet, nor have potential systematic backgrounds been rejected.

## 6 CONCLUSIONS

Axions are a well-motivated dark-matter candidate, enjoying both a bounded parameter space as well as experiments capable of

searching a large portion of that region definitively. Quantum-limited SQUID amplifiers and Rydberg atom single-quantum detectors will give microwave-cavity axion detectors sensitivity to the most feebly coupled axion models. At the same time, new high frequency cavity designs may extend the mass coverage by at least another decade.

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